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Design of a solid-scintillator based Neutral Current Detector.

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1. Introduction.

Our proposed design for a neutral current detector is based on the idea of thin layers of ^{6}Li sandwiched between scintillator layers, such as CsI. ^{6}Li has a very large cross section for thermal neutrons (940 barns), giving rise to the reaction

$$n + {}^6\text{Li} \Rightarrow {}^3\text{H} + {}^4\text{He}\,. \qquad (1)$$

The triton and the alpha particle will move in opposite directions and produce light pulses in the adjoining scintillators that will be detected in coincidence.

This design would have the following advantages:

1. Neutral-current events can be detected in real time, which is crucial if we want to study time-variations of the solar neutrinos, not to mention the possibility of stellar collapses.
2. Preliminary studies show that background can probably be reduced to manageable proportions, thanks to the coincidence method employed.
3. Neutron counters based on this design can probably be made relatively compact and will not interfere appreciably with the detection of the Cerenkov signals.
4. The handling of these counters will probably not present major difficulties.

We have studied some of the parameters required to come up with a realistic neutron detector based on our ideas. Also, a test bench has been set up to study the practical feasibility of this design. In the following paragraphs we will describe some of the results obtained so far.

2. Optimization of ^{6}Li thickness.

To detect an event, the 2 particles resulting from reaction (1) must emerge from the Li-layer and deposit enough energy in the scintillators to be recorded. We have assumed that this requires about 0.1 MeV. The detection efficiency per captured neutron as a function of thickness of the ^{6}Li layer is shown in Fig. 1. This efficiency decreases from 100% for an infinitely thin layer from which all particle pairs emerge and are counted, to 0% for lithium layers thicker than the combined ranges of the triton and alpha particle, which is 154 μ.

To obtain the total efficiency of the detector, one must multiply the detection efficiency per captured neutron by the neutron capture probability. The latter increases with thickness nearly linearly for the thicknesses considered here which are small compared with the capture mean free path of a neutron in ^{6}Li (230 μ). The increasing capture probability combined with the decreasing detecting efficiency produces a maximum in the overall efficiency, as shown in Fig. 2. The curve peaks in the range 15-25 μ, where the overall efficiency is about 3.5 percent.

For the sake of this discussion we have chosen a standard value of 15 μ. We also assume that counter elements will consist of about 10 layers ^{6}Li alternating with scintillators, for a total ^{6}Li width of 150 μ. This is smaller than the neutron m.f.p. in ^{6}Li, which is 230 μ, so that the detectors are not black to neutrons. The efficiency of the 10-layer sandwich will then be about 35%.

A scatter plot of the energies deposited in the scintillator layers adjoining a 15 μ lithium layer is shown in Fig. 3. The plot shows what can be expected, namely that the long-range triton deposits an energy close to its maximum value of 2.715 MeV, while the short-range alpha particles deposit anywhere between the assumed cut-off of 0.1 MeV and their maximum energy of 2.045 MeV. A scatter plot of the pulse heights is shown in Fig. 4. Here we assume that the pulse height for a given energy is twice as large for tritons than for α particles [1].

3. Total Surface area of detector elements.

As a reasonable guess, based on previous calculations by D.Paterson et al. [2, 3], we assume that the total mass of ^{6}Li in the detector will be 1 kg. With an assumed thickness of 150 μ one can then calculate the surface area.The result is 144 m^2. This surface area is assumed to be distributed in a fashion so as to ensure high probability of intercepting neutrons in their random walk.

4. Background Calculations.

It is essential that any background be reduced to a rate small compared to the expected signal. Fortunately, most sources of background can probably be eliminated , making use of the coincidence as well as the expected characteristic hit pattern of the light pulses. The latter will be investigated separately. There is, however, one source of background that will mimic the signal: Impurities of ^{238}U and ^{232}Th that are present in the scintillator (assumed to be CsI for the purpose of this calculation) will produce α particles in their decay chains, some of which will traverse the Li-layer and thereby trigger both adjoining scintillators in coincidence.

The effect of the U and Th decay chains in the vicinity of the Li-layer has been simulated. The most prominent daughter elements with their characteristic decay energies were taken into account and the results of simulation runs for U and Th are shown in Fig. 5 and Fig. 6, respectively. The scatter plot to the left shows the distribution of atoms whose decay produces at least one α particle that passes through both scintillators and thereby contributes to the background.

To the right is a pulse height scatter plot of these background events, similar to the one of genuine events shown in Fig. 4. Some of the α's in the decay chains are clearly separated as diagonal bands. Comparing Fig. 4 with Figs. 5 and 6, it becomes obvious that the background can be reduced by making cuts in the two-dimensional plots. Such cuts that would pass most of the real events (Fig. 4) are shown by the heavier dots in two rectangular zones in each plot. These cuts would result in a background reduction by a factor of about 9 in Uranium and 7 in Thorium.

The numbers shown in the upper left hand corner of the figures show the fraction of atoms in the effective layer of CsI whose α's or those of their daughters are detected with and without cuts. The results of these calculations are best expressed as the concentration of impurities that produce a background rate of 1 count per day. Using the cuts indicated, one obtains the following concentrations by weight for a detector of the size described in Section 3:

^{238}U : 2×10^{-13}
^{232}Th : 4×10^{-13}

The reason Thorium is less critical by a factor 2 is due to its longer half-life.

For the purpose of the discussion, we have assumed that the scintillator used will be CsI, since there is a large amount of information available in the literature on its properties, such as pulse height defect and pulse shapes for various particles. It has, however, a relatively large cross section for thermal neutrons and its maximum emission occurs at a rather long wave length. Some of the important properties of this and other promising scintillators are listed in Table I.

5. Pulse Shape Discrimination.

In addition to using the coincidence method to reduce the background one can also employ pulse shape discrimination. It is well known that the time distribution of light output from many inorganic scintillators has a two component structure. The decay time of the faster component and the ratio of the amplitude of the slow component to the fast component are functions of the energy loss of the ionizing particle. Thus if one measures these two quantities for the time distribution of the light output one can determine the type of the ionizing particle which produced the light. This technique can then be used to distinguish between the alphas of the background and the alpha-triton products of neutron capture in ^{6}Li. This will reduce the purity requirements of the scintillating materials to be used in the neutral current detectors.

In particular, the decay time of the fast component (tf) of light from CsI(Tl) is about 400 ns and that of the slow component (ts) is about 4000 ns. A search of the literature shows that one can differentiate electrons and alphas using the amplitude ratio of these two components with an efficiency of more than a factor of ten. This measurement was done [4] for electrons from the beta decay of ^{90}Sr and the 5.48 MeV alphas of ^{238}Pu. The energy threshold of the electrons was 350 keV. Making use of the relative amplitude of the two components, R. B. Owen [5] has shown that one can obtain good particle identification between alphas, protons and electrons for NaI(Tl) as well as for CsI(Tl) although it is difficult to make a quantitative estimate of the discrimination power from his data. Therefore one can make use of these characteristics of the light output to differentiate between the alphas of the background and the tritons emitted from neutron capture on the ^{6}Li.

Winyard et al. [6] have found that one can get good separation between alphas and protons in this energy region for CsI(Na)using a zero crossing method of Pulse Shape Discrimination. Their estimates indicate that one can achieve essentially perfect separation. However when they apply this to CsI(Tl) they are unable to get any separation.

At this stage it is difficult to be quantitative about the amount of discrimination one can get since the literature is not very precise about the effectiveness of this method in this energy range. Most of the recent papers use the technique for higher energies associated with identifying the products of heavy ion reactions and are not precise enough in the low energy region to allow one to make the necessary extrapolations. The early data do not have available the modern high speed time digitizers and therefore do not give a good idea of what is possible with modern techniques.

Therefore we are setting up a facility, which is described in this text, to investigate in detail the time distribution of the light output from a number of inorganic scintillators. This investigation will take into account the time distribution and the relative amplitudes of the light from a variety of likely scintillators. It is hoped that out of this investigation will come a reasonable candidate to reduce the background by as much as an order of magnitude or more. When this is added to the numbers achieved by simulation of $>10^{-13}$ gm/gm one assumes that the purity of the scintillator must be in the range of 10^{-12} gm/gm of Th and U. This then sets the range which must be achieved for the purity of the scintillating materials.

6. Implementation of a Scintillator System

The current best scheme for implementing the ^{6}Li sandwich method to detect the NC neutrons in SNO is very preliminary. We discuss this implementation in a series of steps.

The main element of the design is the use of a ^{6}Li scintillator multi-layered sandwich of about 10 layers. This sandwich will be in the form of long narrow strips (1 cm wide by 10 cm long), the scintillator elements of which are alternatively silvered on opposite edges. They will have thin (100μ) layers of scintillator with very thin layers of ^{6}Li (10-20μ) sandwiched between them. The alpha and the triton will be emitted from opposite sides of the ^{6}Li layers into neighbouring scintillator strips. The light from the scintillator strips will be emitted in opposite directions from opposite edges of the strips and will be detected in bands on opposite sets of the SNO photomultipliers. The distribution should be easily recognized as a coincidence and should be quite distinguishable from the other signals both in distribution and in total light output. The alphas in the bulk of the scintillator will only come out from one edge of the strips and can then readily be rejected.

The width of the layers, the number of layers, thickness of scintillators and thickness of ^{6}Li are parameters which have to be determined on the basis of a number of factors. Some of these factors are: the amount of Th and U in the scintillator, the efficiency with which the alpha and the triton will get out of the ^{6}Li and the fraction of the light which will get out of the edges of the strips to name a few. There are also serious problems in the manufacture of the strips and the tubes which will have to be overcome. Therefore we are in the process of implementing a program of experimentation and prototyping to look at the various problems. We hope to be able to carry out this program over the coming year in order to establish the feasibility and cost of such a NC detection system.

The ^{6}Li is very active and cannot be put into the air or into the water. Therefore it is proposed to put the strips in tubes of lucite and fill the tubes with an inert gas like Ar. The tubes would be tailored in length to fit the inner vessel and have as many of the ten cm long strips in them as are required to fill their whole length. Thus one would have a grid of the neutron detectors which fills the volume of the heavy water at a grid size which will be calculated to give about 50% capture of the neutrons produced in the D_2O. It would be hoped that one would be able to arrange for a mechanism to insert and remove the tubes (perhaps similar to the one proposed by the Los Alamos group for their proportional counters) allowing for easy measurement of the effect of the tubes on the experiment.

There are many unsolved problems in this proposed implementation and therefore this system is presented for purposes of discussion only.

7. Test Bench.

A test bench has been assembled for the purpose of studying the response characteristics of various scintillators to different ionizing particles. The test bench consists of a light tight box containing two photomultiplier tubes (type Phillips XP2232B), having type D (Sb-K-Cs) photocathodes. These photomultiplier tubes are specified to have a peak response at a wavelength of approximately 400 nm, and a quantum efficiency of 25%. A simple cosmic ray veto over the light tight box eliminates most cosmic ray events.

Scintillating crystals are mounted on light pipes, attached to the faces of the two photomultiplier tubes. These photomultiplier tubes face toward each other, observing opposite sides of the intervening scintillating crystal. In the event of a neutron capture on ^{6}Li, where the lithium layer is sandwiched between two thin scintillating layers, the photomultiplier tubes will separately observe the scintillation light caused by the resultant alpha and triton reaction products.

The signals from the anodes of the photomultiplier tubes are each fed to an analog-to-digital converter having 8 (soon to be 10) bit resolution measuring one picocoulomb per count), and to a flash ADC. The flash ADC's sample the signal at a rate up to 100 MHz., allowing for 10, 20, 50, ... ns wide records. Each record has 8 bit resolution at 1 picocoulomb per count, and from 256 to 32768 contiguous records are taken at each event. Typically, the first 25% of the records are taken immediately prior to the event trigger, ensuring full capture of the entire event.

The event trigger is derived from coincident signals from both photomultiplier tubes, suitably discriminated against noise. While records are taken in the flash ADC prior to the event trigger, the anode signals to the ADC's are delayed in consideration of the electronic delays in derivation of the event trigger signal.

The ADC's and flash ADC's are contained in a CAMAC crate, together with gate generator logic to latch up on event triggers and to prevent retriggering until event recording is complete. The CAMAC crate is under the control of a 25 MHz PC having a 386 processor, a 287 co-processor, 4M RAM, and hard drives, and networked via ethernet to the Vax 6310 computer. Option setting (record width, number of records per event, etc.) are under program control. Files are recorded and transferred to the Vax for analysis. These files contain the recorded event sizes from each ADC, and all consecutive records from each flash ADC for each event.

This apparatus will be used to observe and record background alpha particle activity, and coincident alpha and triton signals from neutron capture on ^{6}Li sandwiched between various scintillating layers. Scintillators under study include ^{6}LiI, CsI, BGO, BaF_2, and such others as are deemed interesting.

Thorough analysis of alpha particle and triton signatures will be undertaken, in both pulse magnitude and pulse shape.

8. Conclusion.

The results and ideas described in this report seem to us sufficiently encouraging to be further pursued. This will require a number of detailed studies that we intend to undertake in the near future, such as:

1. Investigate the Uranium and Thorium content of promising scintillation materials, establish contact with the manufacturers and find out the extreme limits to which such material can be purified.
2. Investigate the possibility of mass producing these materials in thin slabs of thickness between 0.1 and 1.0 mm.
3. Study the optics of scintillator sandwiches and the reflectivity of Li coatings.
4. Predict the hit pattern on the PM array to be expected from various configurations of scintillators.
5. Measure the total light output from alphas and tritons as a function of energy for various scintillators.
6. Similarly, investigate the time distribution of these light pulses to lay the groundwork for pulse shape discrimination methods to reduce backgrounds, as described in Section 5.
7. Optimize the configuration of the scintillator lattice.

8. Design a scheme for easy insertion and removal of the lattice elements in the SNO detector.

It is clear from this list, which is probably not exhaustive, that a considerable effort will be necessary to come up with a workable design. In view of the importance of the NC detection, we feel, however, that such an effort is fully justified.

References.

[1] Peck et al., Rev. Sc. Instr. <u>30</u>, 703, 1959.

[2] D. Paterson, "Studies of a novel Method for solar Neutrino neutral Current Detection in the Sudbury Neutrino Observatory", M.Sc.Thesis, Carleton University, 1989.

[3] "Solar Neutrino neutral Current Detection Methods in the Sudbury Neutrino Observatory", by C.K. Hargrove and D.J. Paterson, SNO-STR-90-104.

[4] A.A. Gusev and G.I. Pugatcheva, Instruments and experimental Techniques, **31** **(1,PT.1)**, 64, 1988.

[5] R.B. Owen, Nucleonics, 92, 1959.

[6] Winyard et al., NIM, **95**, 141, 1971.

Table I.

Some Properties of Scintillator Candidates.

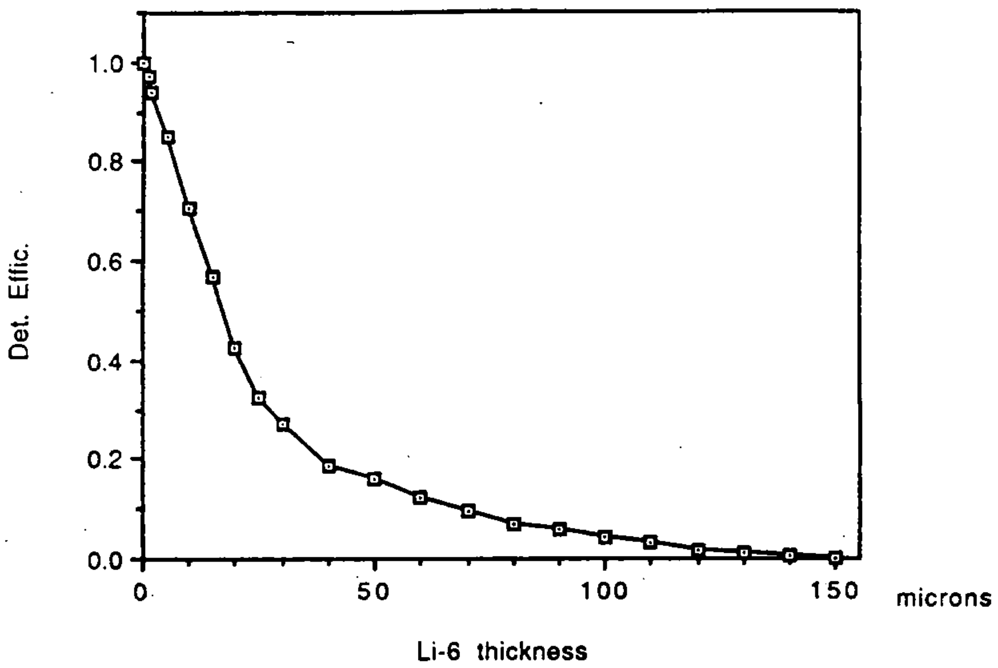
(The examples chosen are all insoluble in water.)

Material	Wavelength max. emission (nm)*	Decay const. (μs)*	Scintillation cutoff wave length (nm)*	Index of refraction*	Density (g/cm^3)*	avge. Light Yield (photons/ MeV) **	Thermal neutron absorption m.f.p.(cm)
CsI(Tl)	565	1.0	330	1.80	4.51	51,800	2.66
B.G.O.	480	0.30	350	2.15	7.13	8,200	39.5
BaF_2	325	0.63	134	1.49	4.88	9,950	48.9
CaF_2(Eu)	435	0.94	405	1.44	3.19	23,650	90.2

* from the catalogue of Harshaw Radiation Detectors.

** I.Holl, E.Lorenz, and G. Mageras, IEEE Transactions on Nucl. Sc., **35**, 105 (1988).

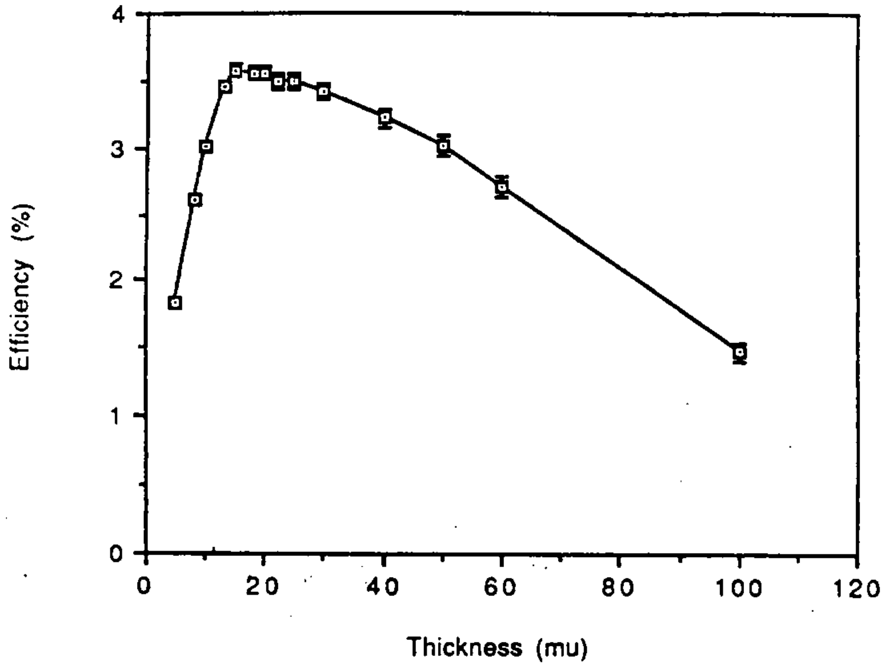
Detection Efficiency vs. Li layer thickness.



D.K.

Figure 1.

Calculated Efficiency of Li-6 Counter.



D.K.

Figure 2.

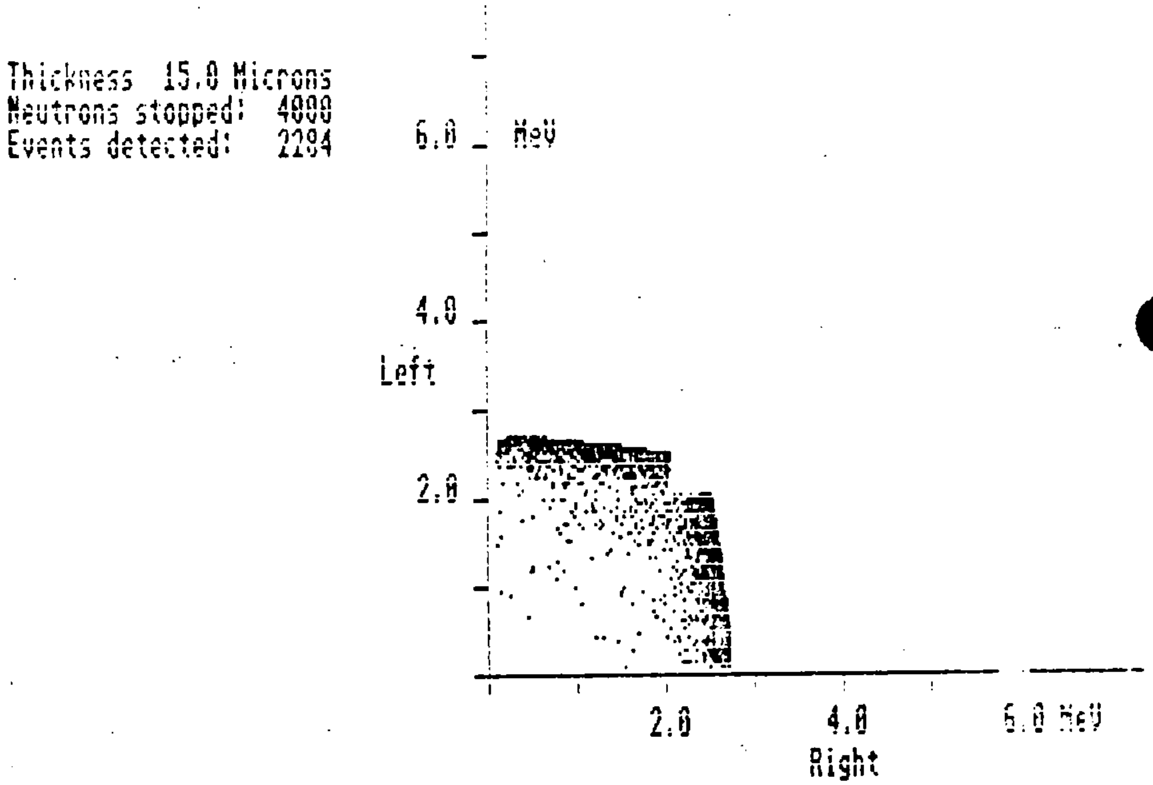

Thickness 15.0 Microns
Neutrons stopped: 4000
Events detected: 2284
6.0
MeV
4.0
Left
2.0
2.0
4.0
6.0 MeV
Right

Figure 3.

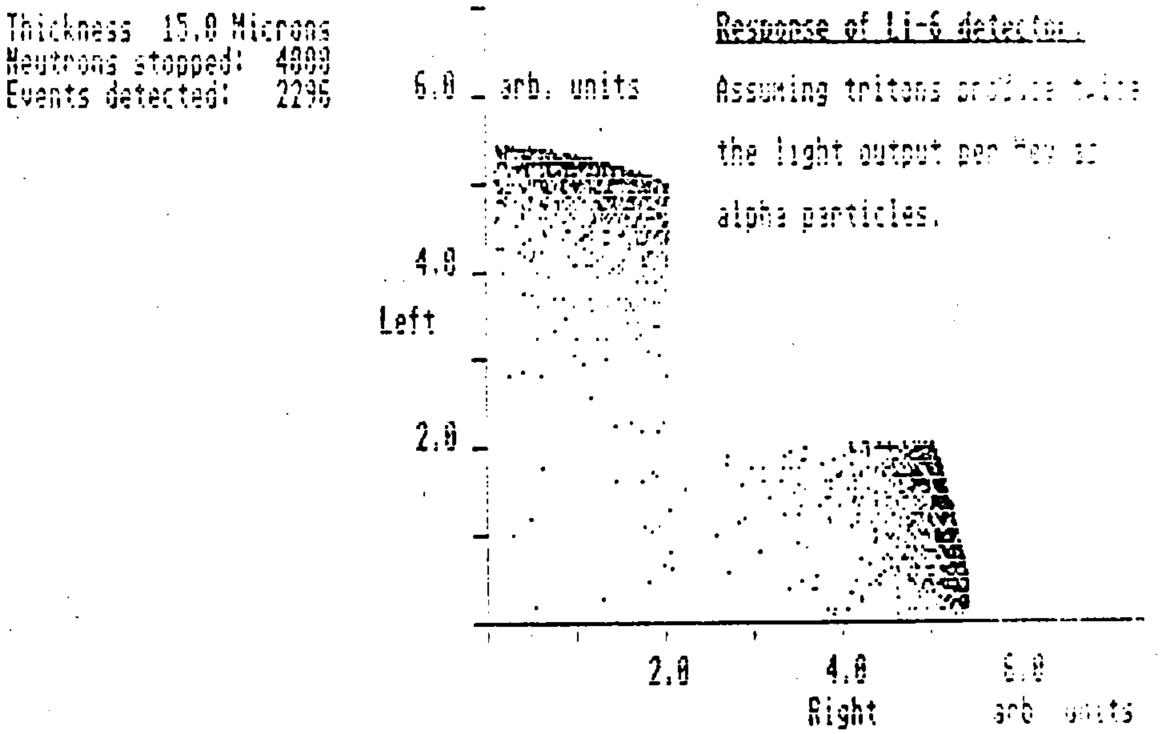
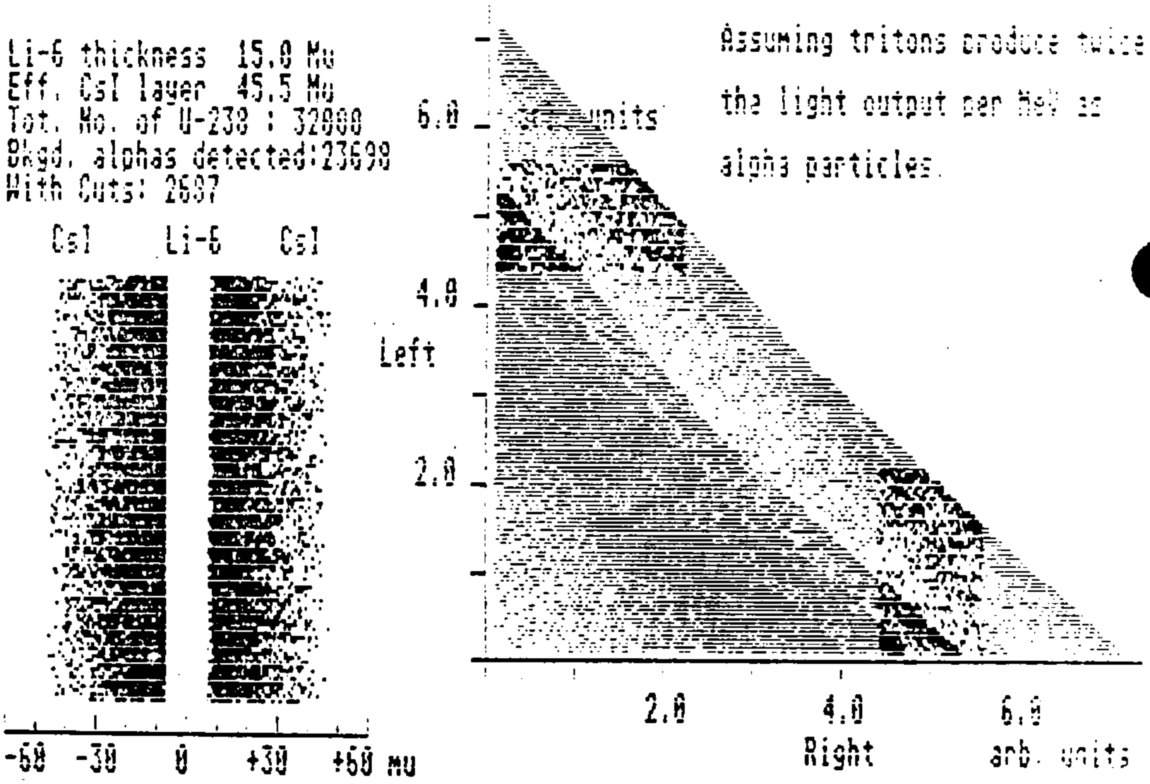

Thickness 15.0 Microns
Neutrons stopped: 4000
Events detected: 2295
Response of Li-6 detector.
Assuming tritons produce twice
the light output per MeV as
alpha particles.
6.0
arb. units
4.0
Left
2.0
2.0
4.0
Right
6.0
arb. units

Figure 4.



U-238 Background

Assuming tritons produce twice the light output per MeV as alpha particles.

Li-6 thickness 15.0 Mu
Eff. CsI layer 45.5 Mu
Tot. No. of U-238 : 32000
Bkgd. alphas detected:23698
With Cuts: 2697

Figure 5.

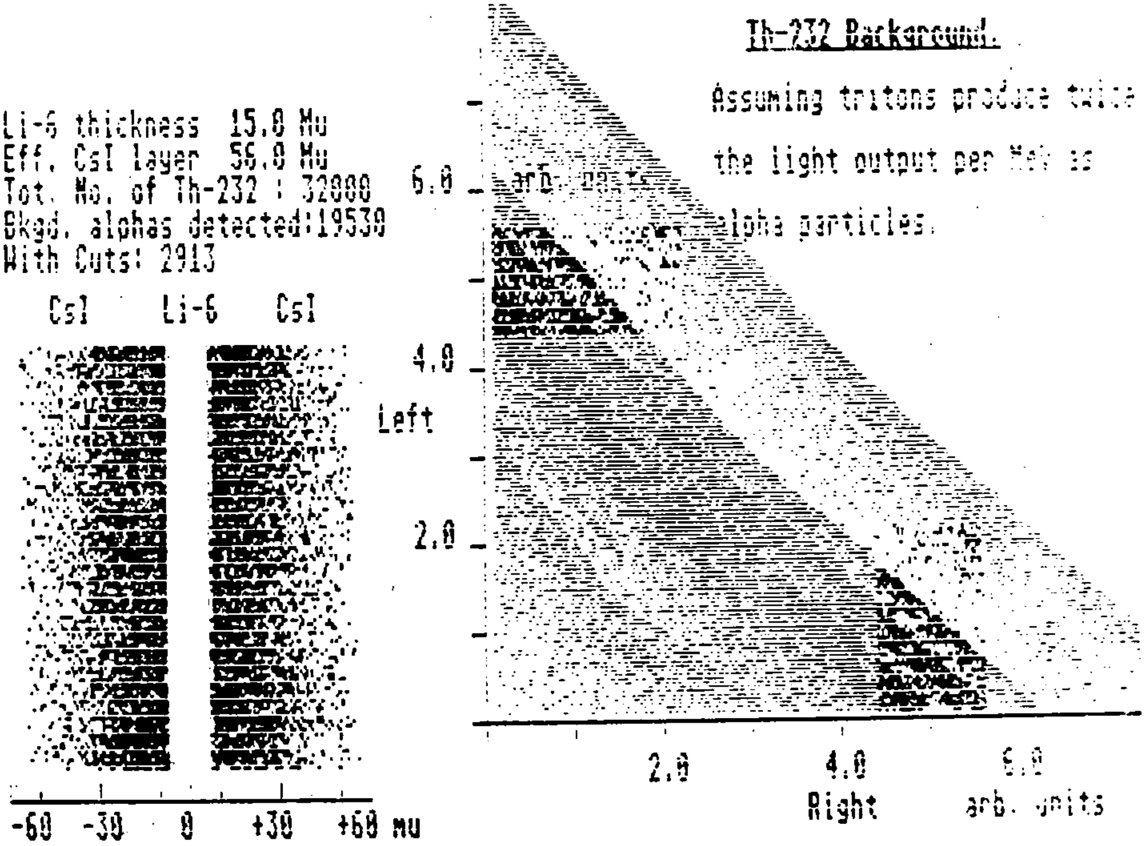

Li-6 thickness 15.0 Mu
Eff. CsI layer 56.0 Mu
Tot. No. of Th-232 : 32000
Bkgd. alphas detected:19530
With Cuts: 2913
CsI
Li-6
CsI
-60
-30
0
+30
+60 mu
Th-232 Background.
Assuming tritons produce twice
the light output per MeV as
alpha particles.
6.0
arb. units
4.0
Left
2.0
2.0
4.0
Right
6.0
arb. units

Figure 6.